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THE DESIGN AND TESTING OF AN ALL-LENS SCHLIEREN SYSTEM

by

Ernest Christian Vogt

January 1957

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THE DESIGN AND TESTING OF AN ALL-LENS

SCHLIEREN SYSTEM

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THESIS

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For the Degree of

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PREFACE

The subject for investigation was chosen because of the need for a schlieren system for the axi-symmetrical wind tunnel operated under Naval Ordnance Contract 16498, Task UTX-2-A, at the Defense Research Laboratory, The University of Texas. The system is required to have good sensitivity and relatively high magnification, yet remain compact and simple as possible. By the use of lenses the system is of the single pass type which gives a fairly high light intensity for photography even after the light has been monochromatized. A single pass system requires only a single path optic bench which can be readily adapted and easily adjusted to any wind tunnel installation.

In contacting various wind tunnel installations throughout the United States, it was discovered that most of them used the conventional parabolic-mirror type schlieren system which is usually quite large and expensive.

This lens type system is designed to be used with a wind tunnel with a small field of view, that is, a tunnel having a test section of small height and length. The system is by no means the best type but is usable and of fairly good quality.

Acknowledgment is gratefully extended to Mr. William H. Shutts and Mr. John L. Harkness for their valuable counsel; and to Mr. Emmett F. Hawley and Mr. Albert P. Sammelson for construction in the machine shop.

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CHAPTER I

THEORY OF SCHLIEREN SYSTEM

Schlieren comes from the German word "schliere" used in glass technology to describe streak or striation in which the refractive index differs from the value in the surrounding field.

"The schlieren apparatus is an optical instrument that is used in the study of supersonic flow phenomena. With this instrument photographs are taken in which the pattern and intensity of the light and dark areas are a measure of the density gradients in the field of view," (Ref. 3).

In theory it is sometimes possible to use schlieren systems to quantitatively measure the density gradients in the flow, but there are usually practical difficulties in this, and in aerodynamics they are most commonly used to show the positions and shapes of regions of shock waves and in boundary-layers and wakes (Ref. 7).

The best-known schlieren methods are the Toepler system and direct-shadow technique, which is usually attributed to Dvorak; both were developed in the second half of the 19th century. The complete history and development of these different types of schlieren systems are discussed in Reference 5. Such methods are of great assistance in building up a physical understanding of the flow, and enable a relatively large field to be examined rapidly and without the introduction of the disturbances produced by exploring instruments. When used in conjunction with high speed photography they are also valuable for observing and recording unsteady flows, (Ref. 7).

The principal elements of the Toepler schlieren method using lenses are shown in Figure 1. The following is the theory of the schlieren system as explained by Liepmann and Puckett, (Ref. 9). The light from a lamp is condensed

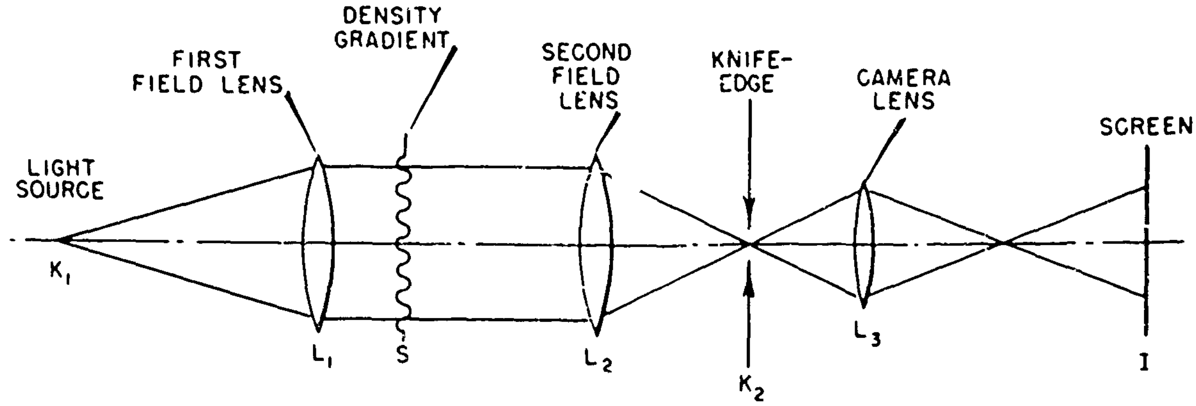

FIG. 1: THE PRINCIPAL ELEMENTS OF THE TOEPLER SCHLIEREN METHOD USING LENSES

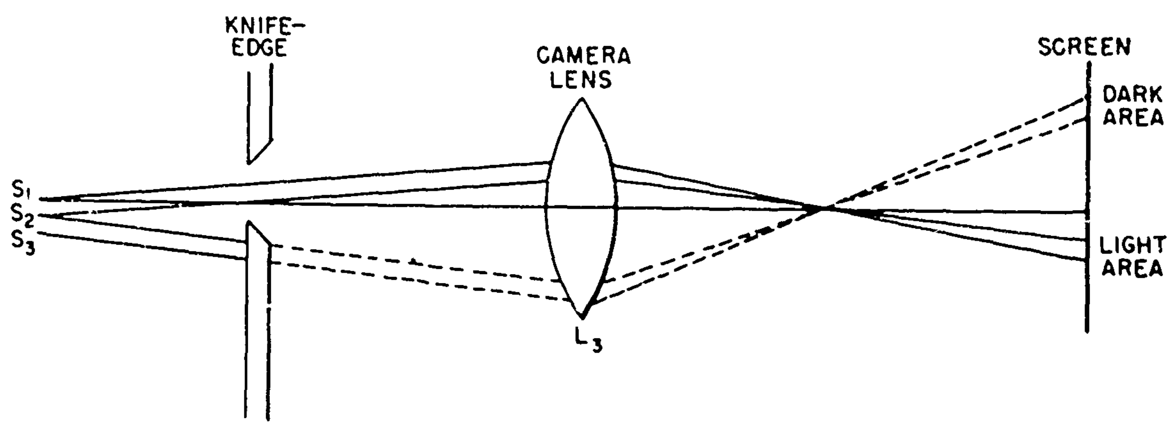

FIG. 2: CAPTURE OF DEFLECTED LIGHT RAYS BY THE IMAGE KNIFE-EDGE

DRL – UT
DWG AA 1877
ECV – CLW
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by a lens to a knife-edge which acts as an adjustment for the intensity and forms a slit which is the effective light source, K_1. The light from the source, K_1, falls on a lens L_1, which produces parallel light. The subject to be examined, for instance a cross section of a wind tunnel, is located at S. Each point of S receives light from all points of the light source K_1, and is thereby uniformly illuminated. Light passes through S, and falls upon the lens L_2, which then converges the light. The lens L_3, then receives the light and forms an image of S, at I, which may be an observation screen or photographic plate. By placing a knife-edge in the focal plane K_2, at the focal point of lens L_2, a fraction of the image of the source is cut off so that only part of the light reaches the screen. If the density in the flow field is uniform across planes normal to the direction of the light, the screen darkens uniformly as the knife-edge is moved across because the images of the source, associated with the light passing through individual regions of the flow field, are coincident at K_2. If the knife-edge is introduced into the light path ahead of or behind the focal point K_2, the image I, will not darken uniformly, but the shadow of the knife-edge will appear. At the focal point of lens L_2, and at no other point along the optical axis, does a point receive light from all points of S.

The uniform darkening of I supposes that all light rays from S, pass through K_2, that is, no deflection of light occurs in passing through S. If in the flow there is a density gradient normal to the direction of the light, the beam is deflected towards the region of higher density because the light travels more slowly where the density is greater. If the rays through a particular point are given a small angular deflection, the fraction of this ray intercepted by the knife-edge is not the same as that for undeflected rays.

In Figure 2, the rays from S_2, have been deflected downward and less light escapes the knife-edge. Therfore, when the rays of light are brought to focus again at I, the illumination of that point will be greater or less, depending on the direction of the deflection.

The schlieren method depends upon the principle that the illumination of a point in the image is due to the small deflection of the rays as they are refracted passing through the subject and detected by the knife-edge. Such a small deflection may be caused by a density gradient in the air. The areas of equal illumination in the image I, correspond to areas of equal deflection of the light rays, and hence to areas of equal density gradient in the flow field, S. The knife-edge intercepts only rays deflected perpendicular to its edge; therefore, the system is sensitive only to the component of the density gradient in that direction. By rotating the knife-edge about the optical axis, the density gradients in any plane perpendicular to the axis may be measured.

If the light source is small and the distance from the subject S, to the focal point of lens L_2, is large, a very small angular deflection of the light rays may produce a large change in illumination at I. The sensitivity of the schlieren system is measured by the proportional change in illumination of the image for a given angular deflection of the light rays. Therefore, the effect of increasing the size of the light source and reducing the distance between the subject S, and the focal point of lens L_2, is to decrease the sensitivity of the system.

The sensitivity of the system may be increased by decreasing the slit, that is, to insert the knife-edge farther into the focal point, K_2, in Figure 1. The result is a greater illumination difference in the field. However, the total illumination of the field is also proportional to the slit

width and becomes darker as the knife-edge is inserted. For a desirable image the knife-edge is inserted until the desired sensitivity is obtained, but not so far that the average illumination of the field becomes too low.

A single straight knife-edge is sometimes used but a double knife-edge leaves only a narrow open slit cutting out all stray light. In the case where a double knife-edge is used and the light source image is completely obscured by the knife-edge, only density gradients larger than some particular value will deflect the light rays sufficiently to register on the screen. The image on the screen will appear as a single contour line along which the density gradient is constant, if the light source image is very small, of the same order as the width of the image knife-edge slit.

Various lens arrangements may be used to produce the schlieren effect. However, at the present time spherical or parabolic mirrors are preferable to lens. Three reasons for the preference are: (1) inhomogeneities in the glass cause the light to scatter, whereas in mirrors the light never enters the glass; (2) refraction in glass for light of different wave lengths causes chromatic errors, whereas in mirrors this is eliminated for the same reason as stated in (1); and (3) accurate large lenses are more difficult to construct than large mirrors.

In the design of this all-lens schlieren system most of these disadvantages have been eliminated since the system is small and requires only small lenses which are available with good optical quality at relatively small cost. The advantage of this system is its compactness coupled with good sensitivity and magnification.

CHAPTER II

DESIGN OF ALL-LENS SCHLIEREN SYSTEM

I. OPTICAL DESIGN OF SYSTEM

In the design of the optics, the features to be obtained were (1) good sensitivity, (2) good magnification and (3) shortest possible optical path.

The distance between the lamp and the condensing lenses, as well as the distance between the light source knife-edge and the condensing lenses is set by the focal length of the condensing lenses. In the same manner the distance between the knife-edge and the first field lens is set by the field lens focal length.

The distance between the camera lens and the image knife-edge was arbitrarily chosen as 2 inches. The remainder of the distances are calculated from basic lens equations and substitutions made to obtain the desired features. The subscripts 2 and 3 refer to lenses L_2 and L_3, respectively, and u is the subject distance, v is the image distance, and f is the focal length. From basic optics,

$$\frac{1}{u_2} + \frac{1}{v_2} = \frac{1}{f_2} \tag{1}$$

$$\frac{1}{u_3} + \frac{1}{v_3} = \frac{1}{f_3} \tag{2}$$

From Figure 3, the relation below can be written:

$$u_3 = f_2+2-v_2 \tag{3}$$

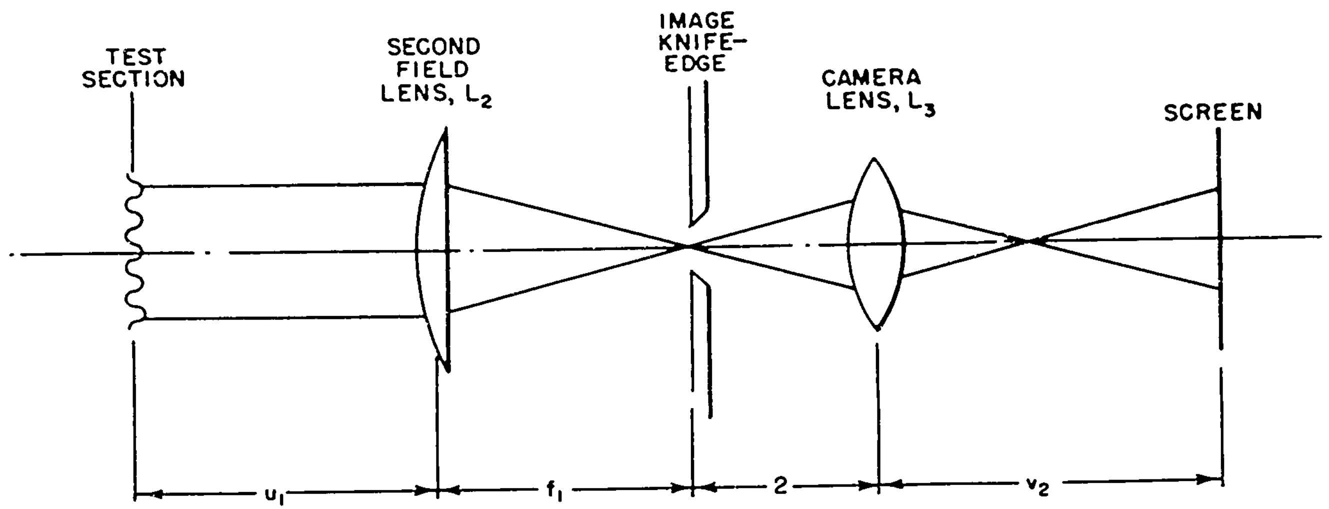

FIG. 3: THE RELATIVE DISTANCES OF THE SECOND FIELD LENS, CAMERA AND SCREEN

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Rearranging equation (1),

$$v_2 = \frac{u_2 f_2}{u_2 - f_2} \qquad (4)$$

To find v_3, as a function of f_3, u_2, and f_2, equation (2) and (3) are combined

$$\frac{1}{f_2+2-v_2} + \frac{1}{v_3} = \frac{1}{f_3}$$

From which

$$v_2 = f_2 + 2 - \frac{v_3 f_3}{v_3 - f_3} \qquad (5)$$

Rearranged in terms of v_3,

$$v_3 = \frac{f_3(f_2^2 + 2f_2 - 2u_2)}{(f_2^2 + 2f_2 - 2u_2) + f_3 u_2 - f_2 f_3} \qquad (6)$$

Now v_3, is obtained as function of u_2, f_2, and m, where m is the magnification of the complete system. The magnification of the second field lens for $u_2 > f_2$, is

$$m_2 = \frac{v_2}{u_2}$$

and the magnification for the camera lens is

$$m_3 = -\frac{v_3}{u_3}$$

By definition the total magnification is

$$m = m_2 m_3 = -\frac{v_2 v_3}{u_2 u_3} \qquad (7)$$

For $u_2 < f_2$ and $-v_2+f_2+2 > f_3$, the magnification for the second field lens is,

$$m_2 = -\frac{v_2}{u_2}$$

and the magnification for the camera lens is

$$m_3 = \frac{v_3}{u_3}$$

By definition again the total magnification is

$$m = m_2 m_3 = \frac{-v_2 v_3}{u_2 u_3} \tag{8}$$

By combining equation (3) and (4)

$$u_3 = f_2+2-\frac{u_2 f_2}{u_2-f_2}$$

which can be written

$$u_3 = \frac{2u_2-2f_2-f_2^{\,2}}{u_2-f_2} \tag{9}$$

Substituting equation (9) into equation (7) or (8)

$$m = \frac{\left(\frac{u_2 f_2}{u_2-f_2}\right) v_3}{u_2\left(\frac{2u_2-2f_2-f_2^{\,2}}{u_2-f_2}\right)}$$

which reduces to

$$v_3 = \frac{m}{f_2}\left(f_2^{\,2}+2f_2-2u_2\right) \tag{10}$$

Eliminating v_3 in equations (6) and (10),

$$m\,(f_2^{\,2}+2f_2-2u_2)+f_3u_2-f_2f_3 = f_2f_3 \qquad (11)$$

Solving for f_3 in equation (11),

$$f_3 = \frac{m(f_2^{\,2}+2f_2-2u_2)}{(f_2+mf_2-mu_2)} \qquad (12)$$

By assuming u_2 as 20 inches for good sensitivity and f_2 as 9 inches, the focal length of a lens already available, a plot can be made of m versus f_3. This is shown in Figure 4. A double concave lens with a -7.87 inch focal length was chosen as the camera lens since it was available. From the curve in Figure 4, it can be seen that this gives a magnification of 2.75, which will be sufficient enlargement of the image.

Substituting $f_2 = 9$ inches and $u_2 = 20$ inches, back into equation (1), v_2 may be found

$$\frac{1}{v_2} = \frac{1}{f_2} - \frac{1}{u_2} \qquad (1)$$

$$v_2 = 16.56 \text{ inches}$$

In order to find v_3, the distance from the camera lens to the ground glass screen or photographic plate, $v_2 = 16.56$ inches and $f_2 = 9$ inches are substituted back into equations (3) and (2)

$$u_3 = f_2+2-v_2 \qquad (3)$$

$$u_3 = -5.50 \text{ inches}$$

$$\frac{1}{v_3} = \frac{1}{f_3} - \frac{1}{u_3} \tag{2}$$

$$v_3 = 18.26 \text{ inches}$$

Figure 5, shows the complete optical design of the system. To produce the parallel light through the wind tunnel, the first field lens is located at the focal-length distance from the light source knife-edge. The distance between the first field lens and the wind tunnel is variable but should be kept small to reduce astigmatic errors caused by nonparallel light.

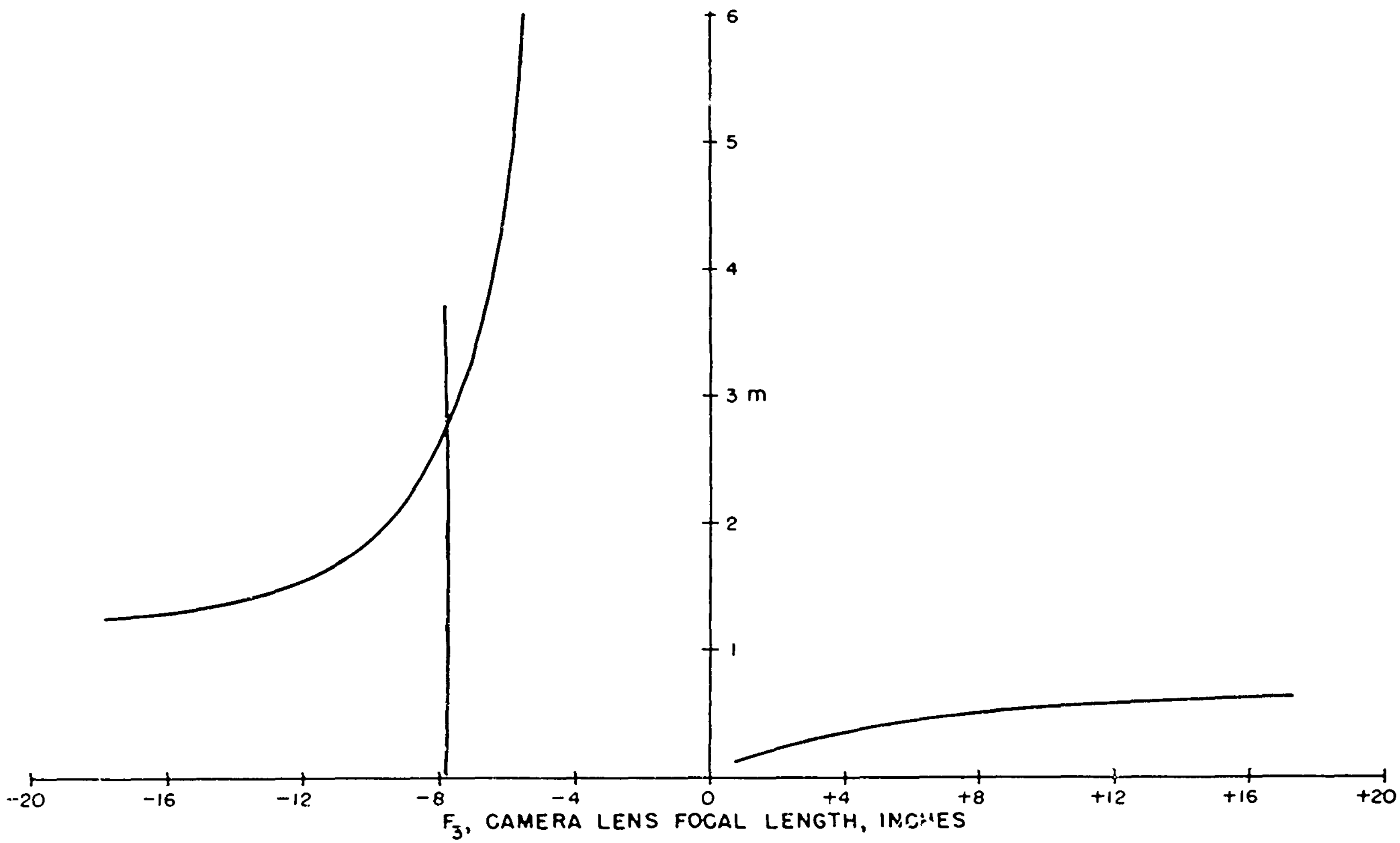

FIG. 4: PLOT OF MAGNIFICATION VERSUS FOCAL LENGTH OF CAMERA LENS

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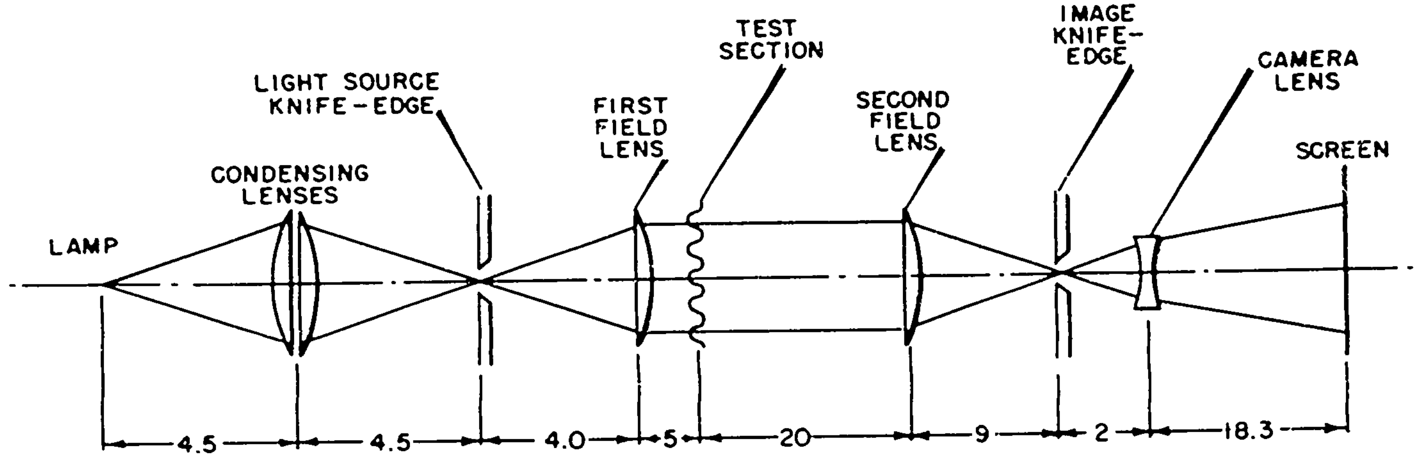

FIG. 5: COMPLETE OPTICAL DESIGN OF THE ALL-LENS SCHLIEREN SYSTEM

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DWG AA 1880
ECV - CLW
11 - 8 - 56

II. MECHANICAL DESIGN OF SYSTEM

Light Source. The schlieren light source constitutes one of the main components of the schlieren system. This light source consists of a mercury vapor lamp, a pair of condensing lens and a knife-edge, distinguished as the light source knife-edge. The light emitted by the knife-edge is the effective light source as considered by the remaining components of the system.

A General Electric A-H6 water cooled mercury vapor lamp rated at 1000 watts is mounted horizontally at the rear of the light source compartment. The A-H6 lamp is approximately $3\frac{1}{4}$ inches overall and constructed of quartz tubing with tungsten electrodes sealed into each end and extending through mercury pools into the lamp. The light-producing portion of the tube is approximately 2 mm inside diameter by 25 mm long.

The initial light output of the A-H6 lamp is 65,000 lumens. The maximum illumination is 195,000 candlepower per square inch, which is almost twenty times brighter than filament sources, and approaches the brightness of high-intensity carbon arcs.

For the proper operation of the Type A-H6 lamp, water must be passed over the quartz tube fast enough to prevent formation of steam bubbles on its surface. To accomplish this, a tube is placed around the lamp, with a very small radial clearance through which the water must flow. Because the cross section of the water passage is restricted, sufficient velocity is obtained to prevent steam formation with input water temperatures up to 120°F. A water flow of about 3 quarts per minute is recommended in order to provide sufficient latitude for some fluctuation in water pressure. Water with a high electrical conductivity may be unsuitable for cooling the A-H6 lamp. The specific resistance should be at least 4000 ohms per cubic centimeter. Leakage current should not exceed 30 milliamperes, (Ref. 1).

The power supply to the 1000 volt transformer required for the A-H6 lamp, is provided with an overload fuse and a pressure switch which will break the circuit if the cooling water pressure is below the minimum. Figure 6, shows the electrical and cooling circuit for the lamp.

The condensing lenses for the light source are two inexpensive plano-convex lenses, 5 inches in diameter with a 4.5-inch focal length.

The design of the knife-edge permits the blades to move the full width of the opening, which provides for the insertion of a screen for the purpose of focusing the light source. By watching the image upon the screen inserted in the knife-edge and adjusting the position of the lamp, a sharp image of the lamp can be obtained. For fine adjustment the knife-edge is provided with a rotary movement about the optic axis. For obtaining the schlieren effect in a different plane the knife-edge can be removed and rotated.

The entire light source assembly is housed in a 6-inch, thin walled brass tube. The A-H6 lamp is inserted in the tube from the side with the water and electrical connections protruding as shown in Figure 7. The finned portion of the back housing provides additional cooling to prevent overheating and thus reduces the possibility of breaking the condensing lenses. Adjustments of the light source are provided in the lamp mounting thus giving both vertical and horizontal movement. The condensing lenses are in a fixed position of 4.5 inches from the lamp along the optic axis and the knife-edge is in a fixed position of 4.5 inches from the condensing lenses.

To prevent the occurrence of chromatic errors introduced by the use of the mercury lamp, a Wratten type 50 gelatin filter is inserted immediately in front of the light source knife-edge. The Wratten type 50 filter, which transmits light of 4360 and 4080 Å, was selected since the A-H6 lamp is predominant in these wavelengths as shown in Figure 8. The intensity of the source is reduced

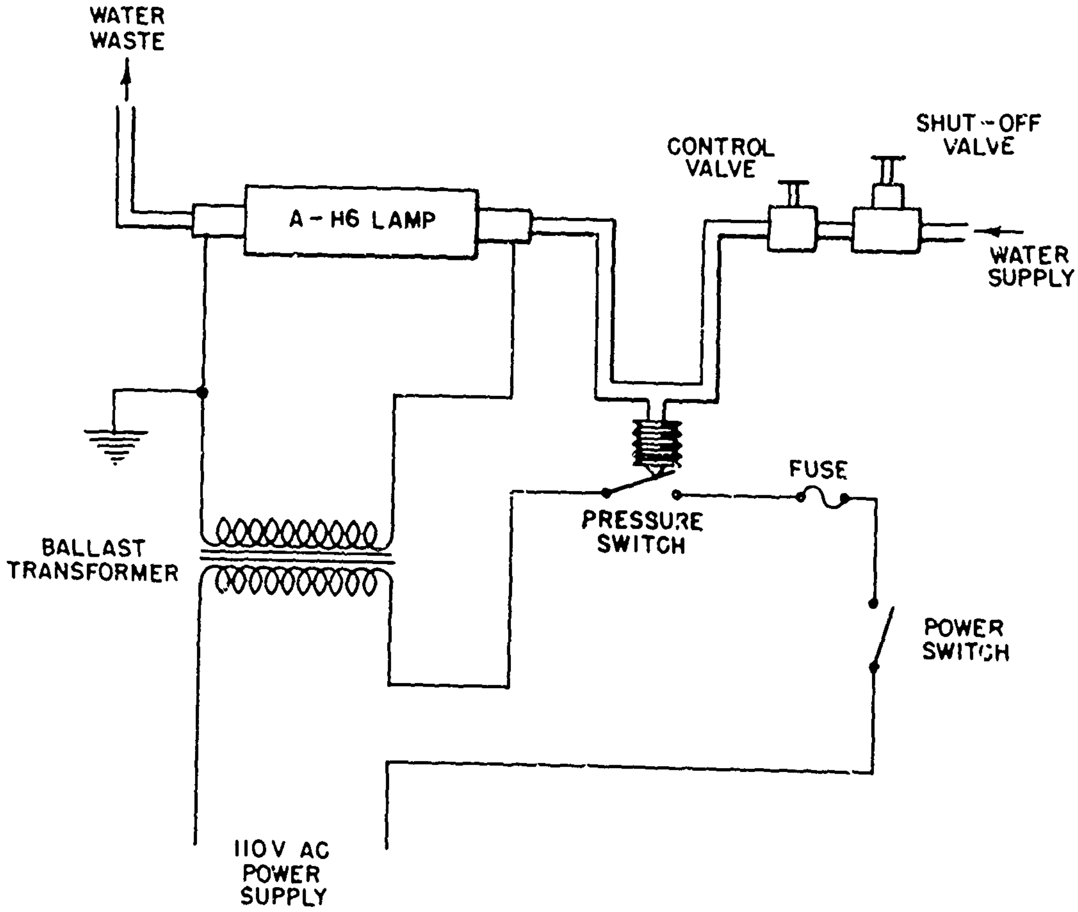

FIG. 6: THE ELECTRICAL AND COOLING CIRCUIT
FOR THE A-H6 LAMP

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DWG AA 1881
ECV - CLW
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1000 WATT WATER COOLED MAZDA AH6 LAMP IN CORNING 774 GLASS JACKET

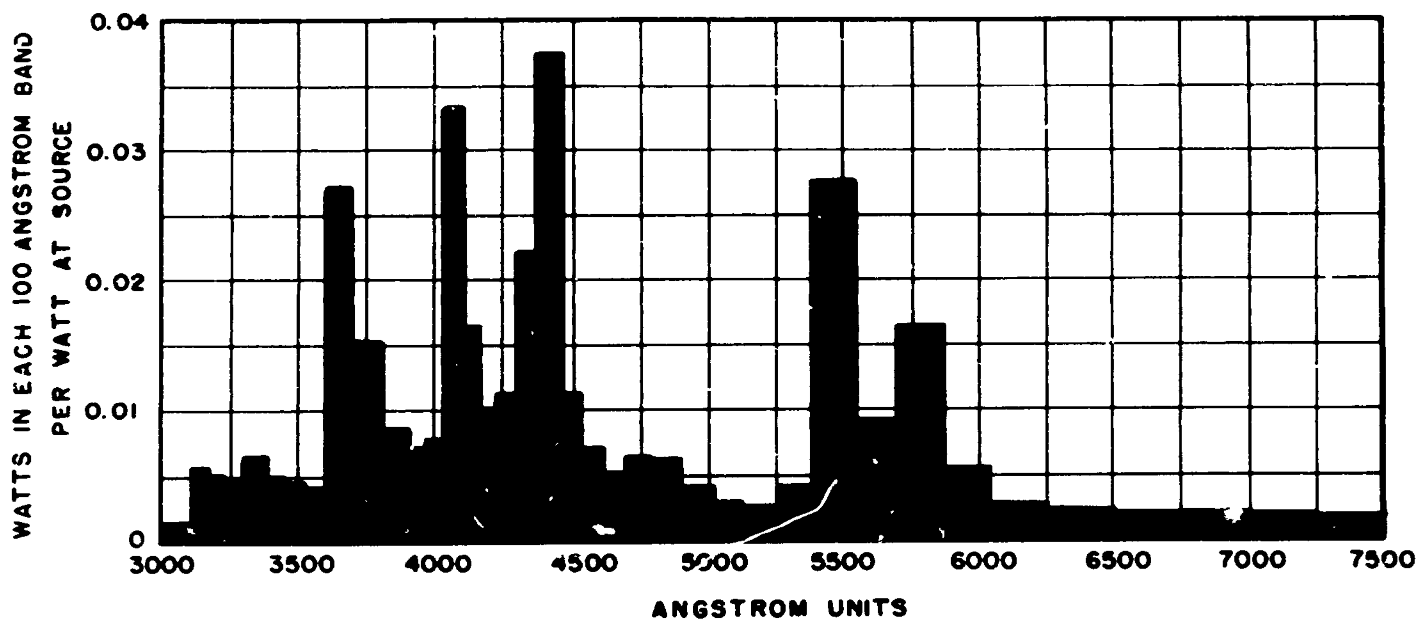

FIG. 8: LIGHT INTENSITY OF AN A-H6 LAMP FOR EACH 100 ANGSTROM BAND

(REF. 1)

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by this filter, but in order to obtain monochromatic light, the intensity of the light source must be sacrificed.

Field Lenses. The optic pieces, except for the field lens (a specially ground lens), are relatively cheap lenses. The original optic piece, tested as the first field lens, was striated, thus causing the light to be dispersed. This lens was of a short focal length. To replace it with a corrected lens of the same focal length, a cost of $1500 was quoted. Since the purpose of this optic piece was to form the parallel light, any focal length could be used which was within reason and the longer focal lengths are much easier to correct. Accordingly, a corrected 5-inch lens with a 40-inch local length was obtained for $150 or 1/10 the price of the corrected short focal length lens. Thus the distance between the light source and the first field lens was increased from 9 inches, as originally planned, to 40 inches.

The second field lens, L_2, is a 5-inch uncorrected plano-convex lens with a 9-inch focal length. Originally the first field lens was of the same quality as the second field lens.

As shown in Figure 9, the field lenses are mounted in aluminum supports which provide rotation in two planes perpendicular to the optical axis. The vertical adjustment is provided by thumb-screws on the lens holder, and the longitudinal setting is accomplished by sliding the support along the optical bench. The lens holders are equipped with removable covers which protect the lens while the system is not in use.

Knife-edges. Both the light source knife-edge and the image knife-edge are of the same construction but the image knife-edge is mounted on a separate pedestal which can be adjusted vertically. The knife-edge construction is shown in Figure 10. The knife-edges are raised or lowered by thumb-screws

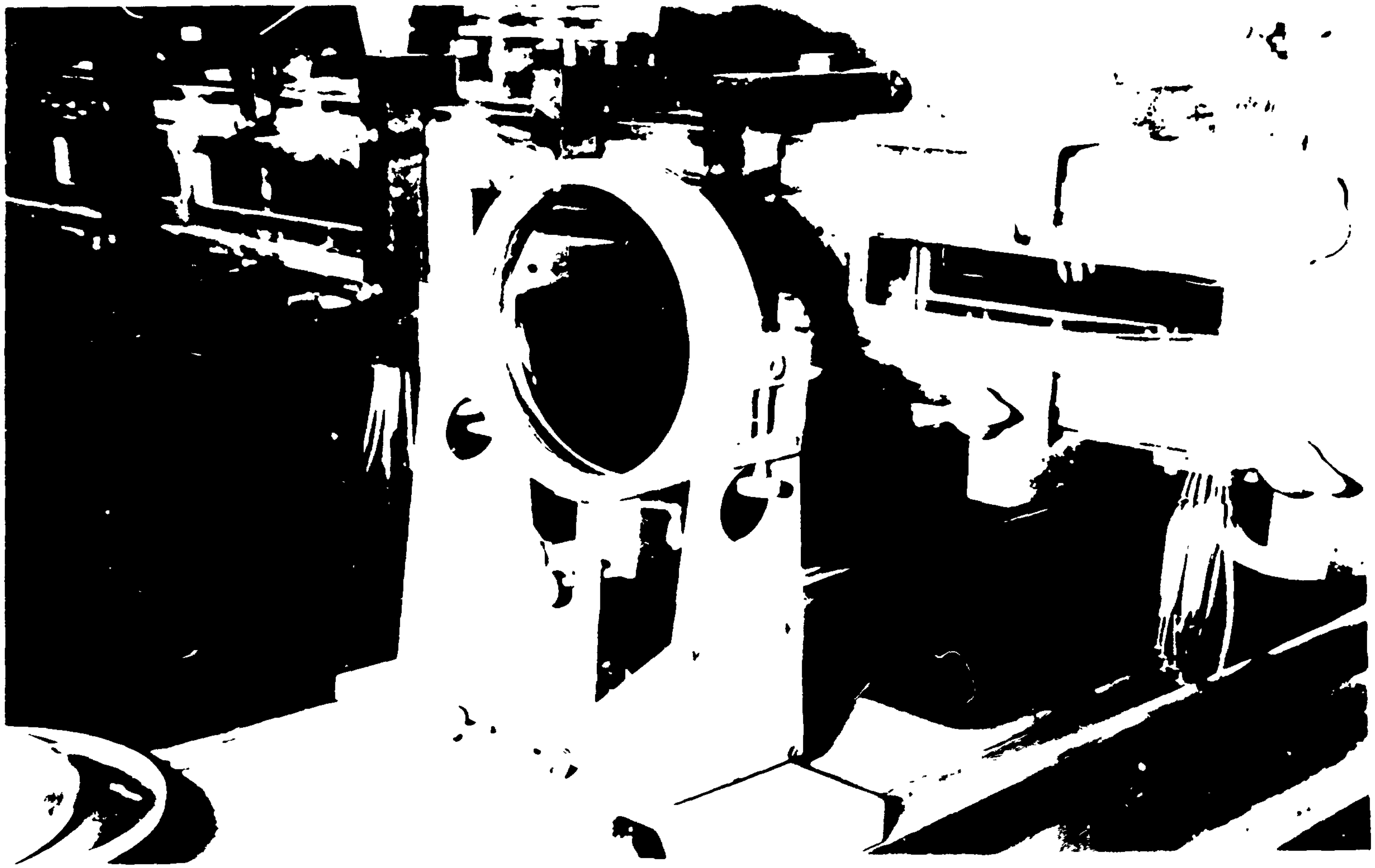

FIG 9. FIRST FIELD LENS SUPPORT

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FIG. 10: KNIFE-EDGE AND CAMERA

which are counter balanced by compression springs to insure positive movement. A fine rotary adjustment about the optic axis is provided by opposing thumb-screws.

Schlieren photographs may be taken of density gradients in a vertical or horizontal plane by cutting the image in the respective plane. In order to align the knife-edge slit vertically or horizontally, the knife-edge assembly is unscrewed from the pedestal and replaced after rotating 90°.

Camera. The camera design is unique in that a double concave lens is used to form the image, making the camera unit only 18 inches long. The usual camera lens is a convex lens and requires distances from 30 to 40 inches to form an image with sufficient magnification.

As shown in Figures 10 and 11, the camera is in two sections. The back section, which holds the ground glass, is rectangular and the front section, which holds the lens and shutter, is cylindrical. The two sections can be moved relative to each other to set the lens to screen distance and be locked in place by means of a split collar on the back section. The shutter is a standard Ilex shutter with speeds of 2 seconds to 1/150 second. The ground glass holder allows a 5x7 film pack to be slipped in place for photographing.

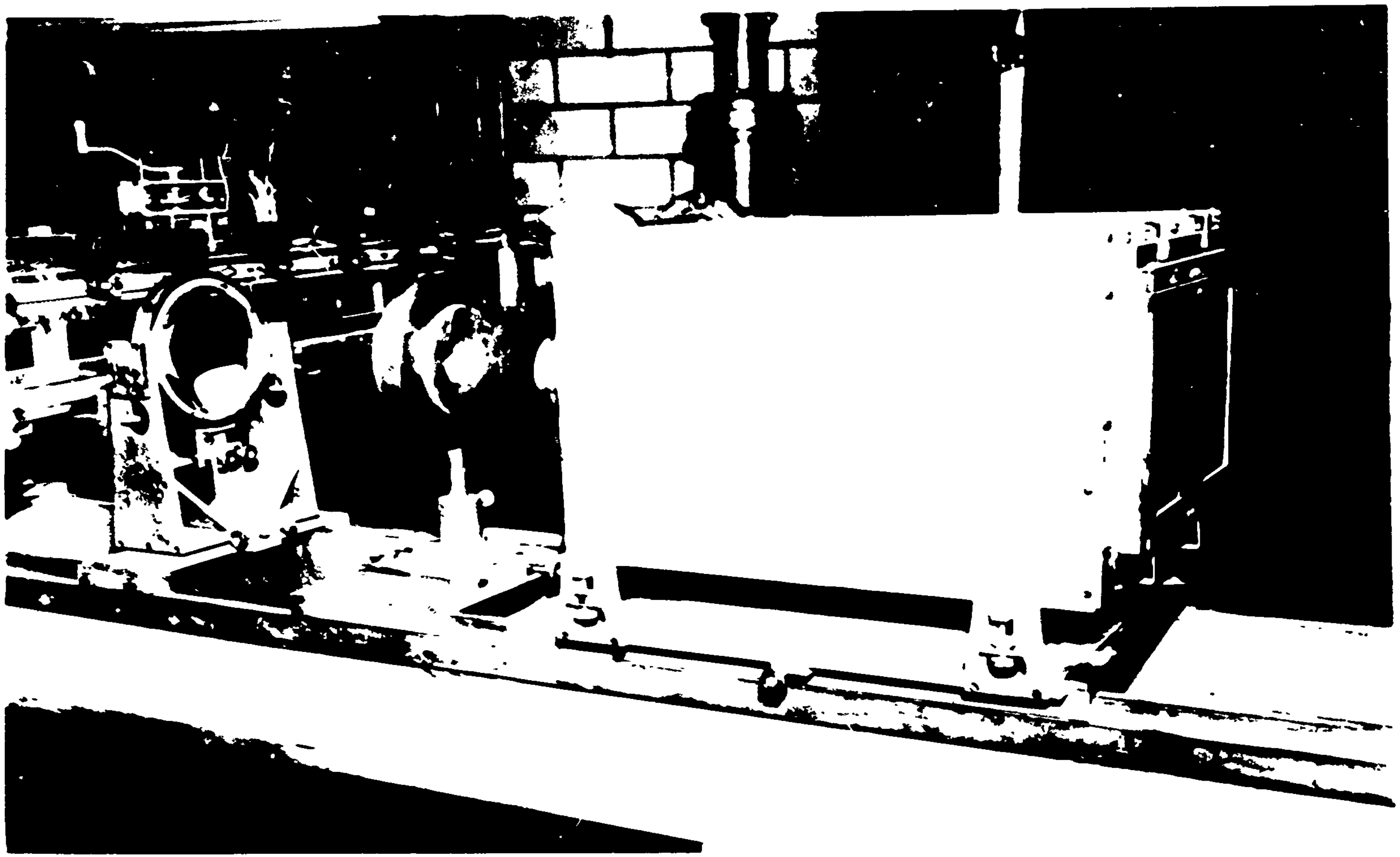

FIG. 11: BACK VIEW OF CAMERA

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CHAPTER III

OPERATING PROCEDURE

OF THE ALL-LENS SCHLIEREN SYSTEM

The following is the operating procedure for the use of the all-lens schlieren system, as used in setting up all tests.

(1) The system is rolled into place and elevated by means of the three screws on each bench stand until the optical axis is at the height of the wind tunnel centerline.

(2) The inlet water hose is connected to the control box outlet and the return water line placed in a drain.

(3) The water valve at the control box should be opened until the pressure switch clicks, indicating the minimum water pressure at which the lamp will operate. The water flow is then measured at the drain to see if it is above the minimum of 3 quarts per minute. This cut-off pressure setting may be changed by adjusting the pressure switch.

(4) The power may now be applied to the lamp. If the lamp housing becomes extremely hot, extra cooling should be provided by blowing air over the finned portion of the housing.

(5) In focusing the light source the knife-edge is opened to the maximum and an onion skin paper screen inserted in the knife-edge plane. While watching the screen, the lamp is adjusted until a sharp image of the lamp is focused on the screen. The paper screen can then be removed and the knife-edges closed to a slit of about 1/64-inch width. The slit-width partially determines the system sensitivity and controls the light intensity.

(6) The first field lens is then set by measuring the exact distance of 40 inches from the light source knife-edge to the center of the lens. The lens is raised and rotated until perfectly aligned perpendicular to the optic axis.

(7) The test section of the wind tunnel may be any distance from the first field lens but is arbitrarily chosen as 5 inches. The distance from the second field lens to the test section is then set at 20 inches.

(8) The image knife-edge is positioned with the light source "On" by moving the pedestal along the optic axis until the smallest, sharp image appears upon the closed knife-edge. The final positioning is done by watching the ground glass screen to see that the screen is uniformly darkened as the knife-edges are moved in and out. The knife-edge slit may be partially set by raising the upper edge and allowing the lower edge to block half of the image. The final adjustments of the edges must be set with a density gradient in the test section so the desired sensitivity and light intensity will appear on the screen.

(9) The distance from the camera lens to the screen should be set at 18.3 inches by sliding the cylindrical front section into the rectangular back section. The camera lens is set about two inches from the image knife-edge or in a position so that a sharp image of the test section will be projected on the screen.

(10) In order to view the screen the camera shutter is set on time and opened. For photographing, when using the filter on the light source, the shutter speed is set from 1/50th to 1/150th second depending on the light intensity. The aperture is set so the image covers the complete screen or until the desired portion of the test section appears on the screen.

CHAPTER IV

TESTING AND RESULTS

A two-dimensional, continuous-flow wind tunnel at nominal Mach Numbers of 1.9 and 3.7 was used to test the all-lens schlieren system. The set up of the schlieren system in the circuit of the two dimensional wind tunnel is shown in Figure 12.

Figure 13 shows the shock wave from a 30 degree cone at a Mach Number of 1.87, as calculated from the ratio of test section static pressure to settling chamber pressure. The shock angle from the 30 degree cone indicates a Mach Number of 1.87, as read from Dailey and Wood (Ref. 6). Figure 14 shows the shock wave from a 12 degree wedge at a calculated Mach Number of 3.5, based on a pressure ratio of 0.0131. The measured shock angles from the 12 degree wedge indicate a test section Mach Number of 3.75, as read from Dailey and Wood. As can be seen the calculated Mach Number is lower than the Mach Number indicated by the shock angles. An explanation of this would be that weak shock waves originating in the nozzle cause the test section static pressure taps to read slightly higher.

The shock wave from a quarter inch sphere at a Mach Number of 1.87 is shown in Figure 15.

The photographs using the all-lens schlieren system indicate fairly good sensitivity although less sensitive than the photograph shown in Figure 16, taken with a parabolic mirror schlieren system. By the use of accurate lenses throughout the lens schlieren system, the sensitivity could be increased considerably. The lens schlieren system does give a magnification of the test section, while the mirror schlieren system actually demagnifies.

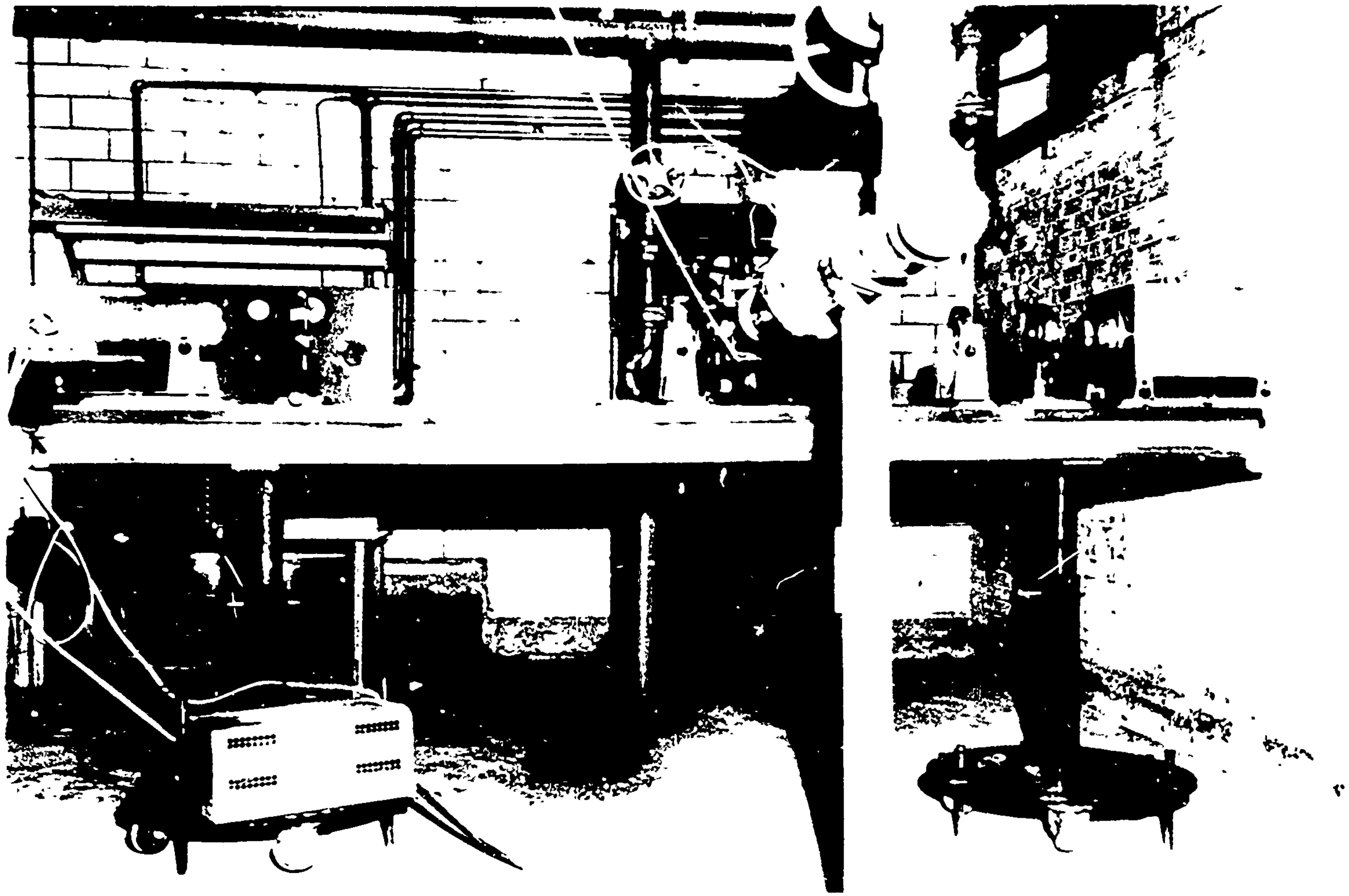

FIG 12 ALL-LENS SCHLIEREN SYSTEM IN TEST POSITION OF THE TWO-DIMENSIONAL WIND TUNNEL

FIG. 13: SCHLIEREN PHOTOGRAPH OF
A 30° CONE AT MACH 1.87

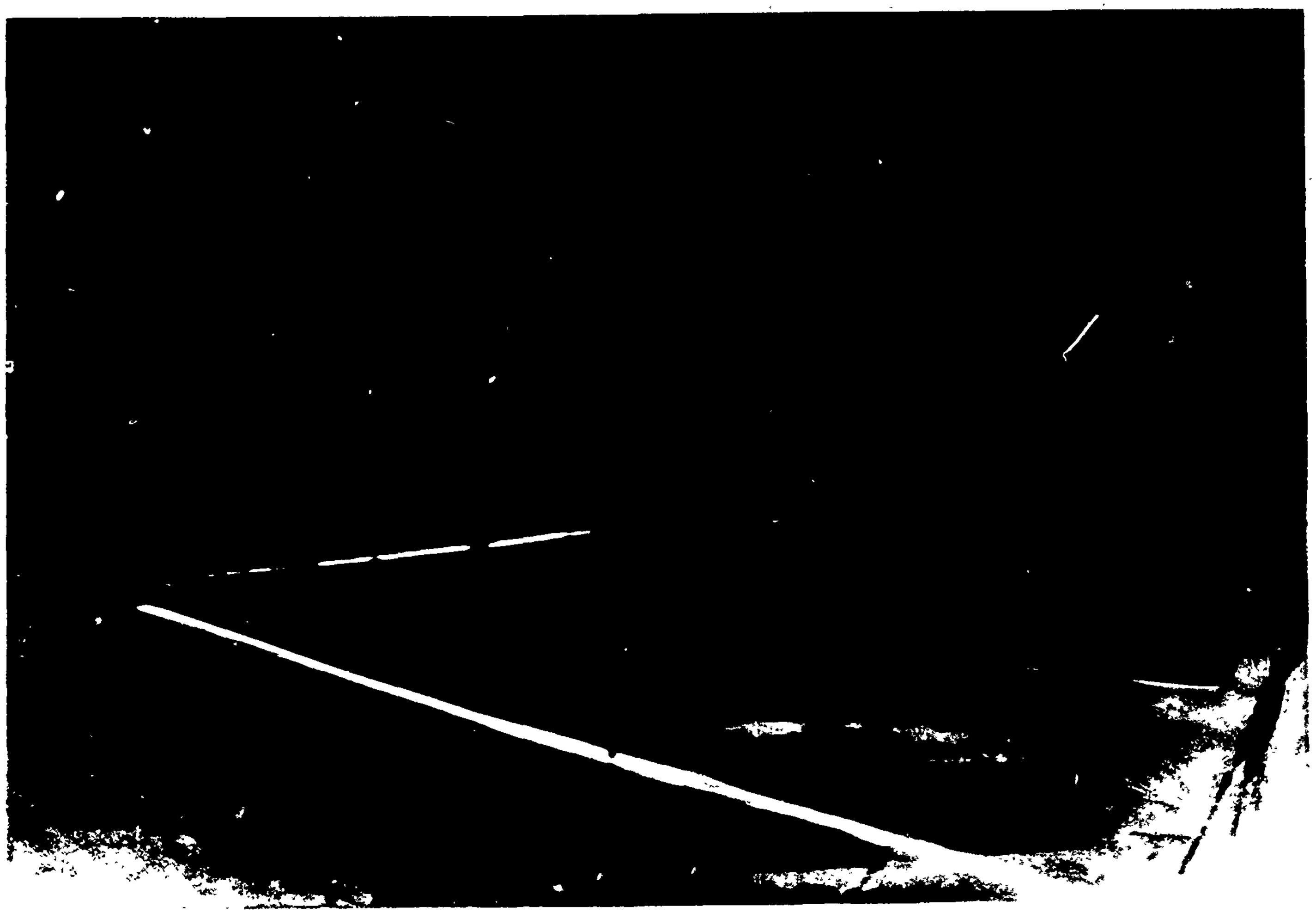

FIG. 14: SCHLIEREN PHOTOGRAPH OF
A 12° WEDGE AT MACH 3.75

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FIG. 15: SCHLIEREN PHOTOGRAPH OF A SPHERE AT MACH 1.87

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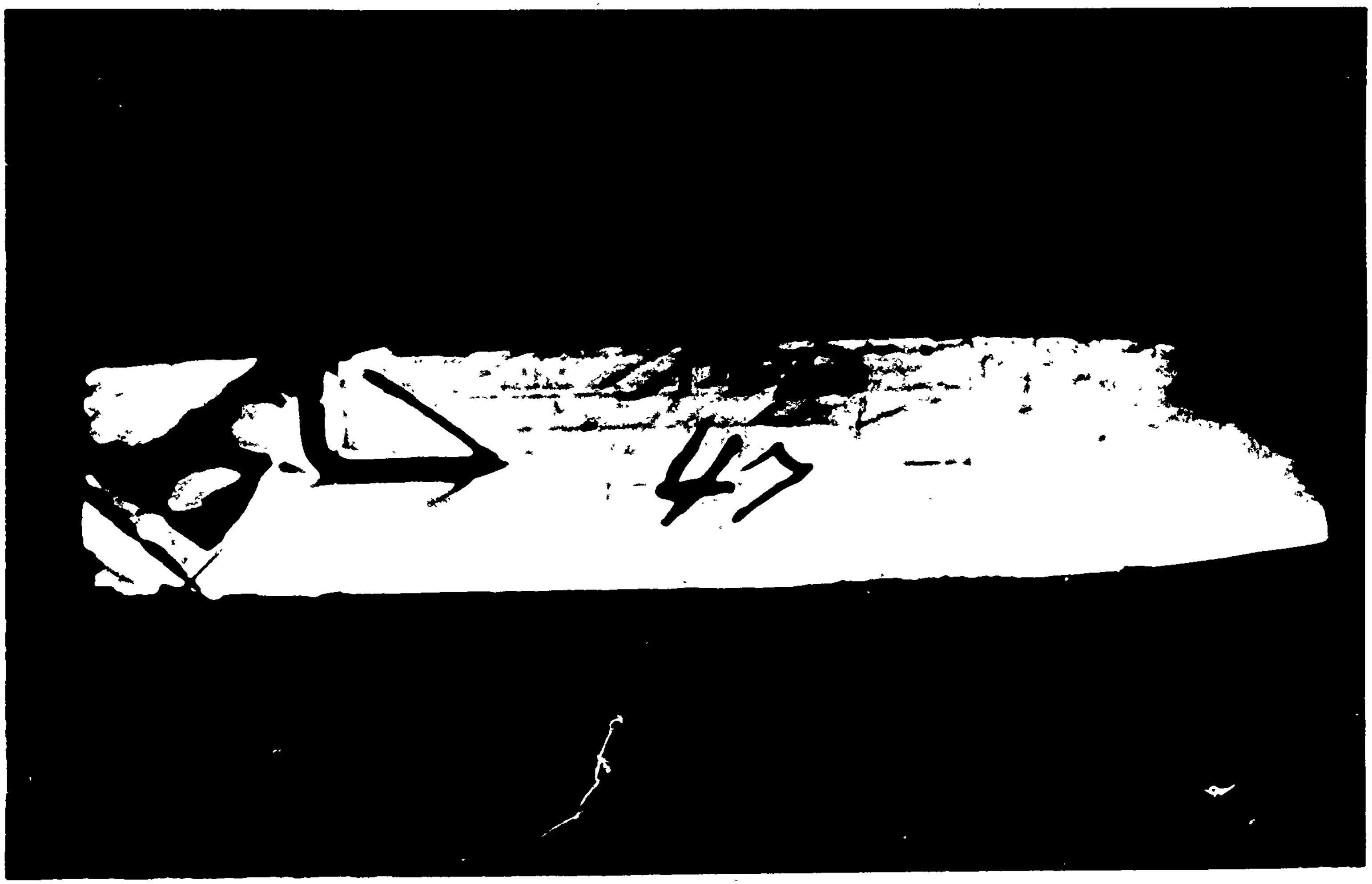

FIG. 16: MIRROR SCHLIEREN PHOTOGRAPH
OF A 30° CONE AT MACH 1.87

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It was found that the calculated positions of the schlieren components were correct. Adjusting of the camera position each time the system was set up was necessary to obtain a sharp image of the test section.

Variation of the light source knife-edge width showed a marked variation in the illumination of the image. When a wide source slit was used the upper and lower parts of the image would appear dark as shown in Figure 17. In this case the image knife-edge would cut off these regions. By using the narrowest slit possible and yet obtaining enough light intensity, an image of uniform illumination may be obtained as in Figure 14. The same type of darkening of the upper and lower parts of the image as shown in Figure 17, would appear, if the image knife-edge was not set exactly at the focal point of the second field lens.

Figure 18 shows the test section with no flow. With this a comparison can be made of photographs taken at supersonic flow, thus making it possible to distinguish the shock waves from the scratches on the glass window. Considerable difficulty was encountered in running the continuous flow wind tunnel in that oil would deposit on the tunnel windows and cause the streamline effect as seen in Figure 13.

The effect of taking photographs with and without a filter is shown in Figures 13 and 19, respectively. Without a filter, Figure 19, the image appears in a hue of colors which will not focus in a sharp image. A longer film exposure time was required for photographing when using the filter to compensate for a lower light intensity. The use of a Wratten type 77A filter instead of the Wratten type 50 filter would give a much higher light intensity and still produce monochromatic light.

The critical adjustment of the system was the setting of the image knife-edge slit. The slit width as well as the portion of the image cut off

FIG. 17: NONUNIFORM DARKENING CAUSED BY A WIDE SOURCE SLIT

16498-A-45

16498-A-46

FIG. 18: PHOTOGRAPH OF THE TEST SECTION
AT NO-FLOW

16498-A-47

FIG. 19: SCHLIEREN PHOTOGRAPH OF A 30° CONE AT MACH 1.87 WITHOUT A FILTERED LIGHT SOURCE

determined the sensitivity. The knife-edge must be set perfectly at the focal point of the second field lens to give uniform darkening of the screen. The trial and error method was the only procedure found satisfactory for setting the knife-edge. At the low Mach Number of 1.87, a suitable image could be obtained at several knife-edge settings, since the density gradients were large, but with the small density gradients across a shock wave at Mach 3.75, a very critical setting was required.

Future improvements of the system would include the use of better lenses and a Wratten type 77A filter.

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